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SOLAR CONCENTRATION PROPERTIES OF FLAT FRESNEL LENSES WITH LARGE F-NUMBERS

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SUMMARY

The solar concentration performances of flat, line-focusing sun-tracking Fresnel lenses with selected f-numbers between 0.9 and 2.0 were analyzed in this study. For an ideal lens with design characteristics similar to those of an existing large NASA test article, lens transmittances, image intensity profiles, receiver target widths, and geometric concentration ratios were studied as a function of f-number. The effects of small, transverse sun-tracking deviations were also evaluated for various f-numbers. The primary measure of concentration effectiveness was taken as the geometric concentration ratio resulting from a target receiver interception of 78% of the incident sunlight on the lens.

Lens transmittance was found to have a weak dependence on f-number, with a 2% increase occurring as the f-number is increased from 0.9 to 2.0. The geometric concentration ratio for perfectly tracking lenses peaked for an f-number near 1.35. Intensity profiles were more uniform over the image extent for the large f-number lenses when compared to the f/0.9 lens results. Substantial decreases in geometric concentration ratio were observed for transverse tracking errors equal to or below 1° for all f-number lenses. With respect to tracking errors, the solar performance is optimum for f-numbers between 1.25 and 1.5.

The experimental procedure of covering outer sections of a test lens to create larger f-number devices was simulated. The method was found to provide accurate information on the effects of f-number on lens solar performance.

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I. INTRODUCTION

The solar concentration properties of flat, line-focusing, tracking, Fresnel lenses have previously been analyzed for lenses with f-numbers less than or equal to one [1-4]. Low f-numbers are particularly advantageous with respect to structural requirements and tracking mechanisms. However, selection of the design parameters for a lens must also be based on the concentration performance of the Fresnel refractor, specifically, the concentration levels achievable and the sensitivities to tracking errors and defocusing. Objectives of the present study include evaluation of lenses with f-numbers between one and two in terms of concentration profiles, required receiver target widths, and solar transmittances for perfectly tracking devices and with small sun-tracking deviations.

An optical model was introduced earlier for assessing the solar concentration performance of flat Fresnel lenses [1]. This model, previously used to analyze NASA test lenses of widths 0.56 and 1.8 meters and f-numbers 1.0 and 0.9, respectively, is applied in this study to larger f-number lenses. In particular, the geometry and groove configuration of the large NASA lens has been selected for use in the analysis to facilitate comparisons with known concentrator performance.

Finally, it is noted that the effects of f-number on solar concentration performance may be studied experimentally by selectively covering outer sections of a single lens, e.g., the large NASA test lens. This procedure is expected to be valid in discovering trends and general characteristics with respect to increasing f-numbers.

However, for such tests, the lens widths and total numbers of serrations vary with f-number while the focal length and hence groove design angles remain fixed. In contrast, a more viable evaluation of the effects of f-number on solar concentration maintains a fixed lens width, identical serration totals, but different focal lengths and hence different groove design angles. Variations in the total number of serrations affect the degree of solar energy localization expected for a given concentrator. Groove design angles determine, in part, the lens transmission properties. Finally, comparative evaluations of image profiles for different f-number lenses is more difficult when the total incident sunlight intercepted is varied.

Determining thru analysis the extent of any deviations between the results obtained by the experimental method and the constant lens width method is a desired outcome of the present study. To achieve this goal, the computerized optical model is used to simulate the experimental procedure.

II. THEORETICAL RESULTS

Based on the analytical model [1], a Fortran-10 computer program was developed to provide data for evaluating the solar concentration performance of lenses with various f-numbers. The lens parameters were selected to correspond with those of the large NASA test lens with the exception of the variable parameters, i.e., the f-number and focal length (Table 1). Lens transmission characteristics, image intensity profiles, receiver target widths, and effects of transverse sun-tracking deviations have been studied for f-numbers 0.9, 1.0, 1.25 1.5, 1.75, and 2.0 and are discussed in the following sections.

TABLE 1. LARGE TEST LENS CHARACTERISTICS

Lens Type	Cylindrical Fresnel, Grooves Down
Material	Rohm and Haas Plexiglas V(811)
Fabrication Technique	Compression Molding
Width	182.9 cm (72 in) Active Aperture 186.7 cm (73.5 in) Total Aperture
Focal Length (for design wavelength)	Variable [Experimental lens-168.0 cm (66.15 in)]
Geometric F-Number	Variable (0.9-2.0) [Experimental lens-0.9]
Center Thickness	0.594 cm (0.234 in)
Groove Density	8.8 cm^{-1} (inner 18 inch panel) 13.2 cm^{-1} (outer 18 inch panel)
Design Wavelength	625 nanometers

A. Lens Transmittance

Under perfect tracking conditions, the total lens transmittance increases monotonically from a low of 86.0% for an f-number of 0.9 to a high of 87.9% for f/2.0. Serration transmission as a function of position, measured with respect to the lens centerline, is illustrated in Figure 1 for f/0.9 and f/1.75. Fresnel reflection losses at the large angle outer serrations are responsible for the nearly 2% drop in lens transmittance for the f/0.9 lens.

The effects of transverse tracking deviations on lens transmittance is neglible for errors $\leq 1°$ for all f-numbers studied. The drop in transmittance for a $1°$ error was 0.25% for f/0.9 and smaller for $1 \leq$ f-number ≤ 2 lenses. Typical changes in serration transmission with tracking error are illustrated in Figure 2 for f/1.75. Transmittances for serrations on one lens half are increased while for the other side, a decrease occurs. For serrations near the lens center on one side of the lens, shading by adjacent groove edges results in a "dip" in the transmittance [1].

Computations of transmittance were based on the optically active width of the lens, i.e., widths of opaque support structures for lens panels are not included.

B. Image Intensity Profiles

Lens dispersion, finite serration widths, and finite solar source dimensions result in a Gaussian-like distribution of concentrated sunlight in the concentrator focal plane. Effects of seasonal or daily variations in direct solar flux are eliminated by expressing the image intensity in terms of a local concentration ratio as a function of position.

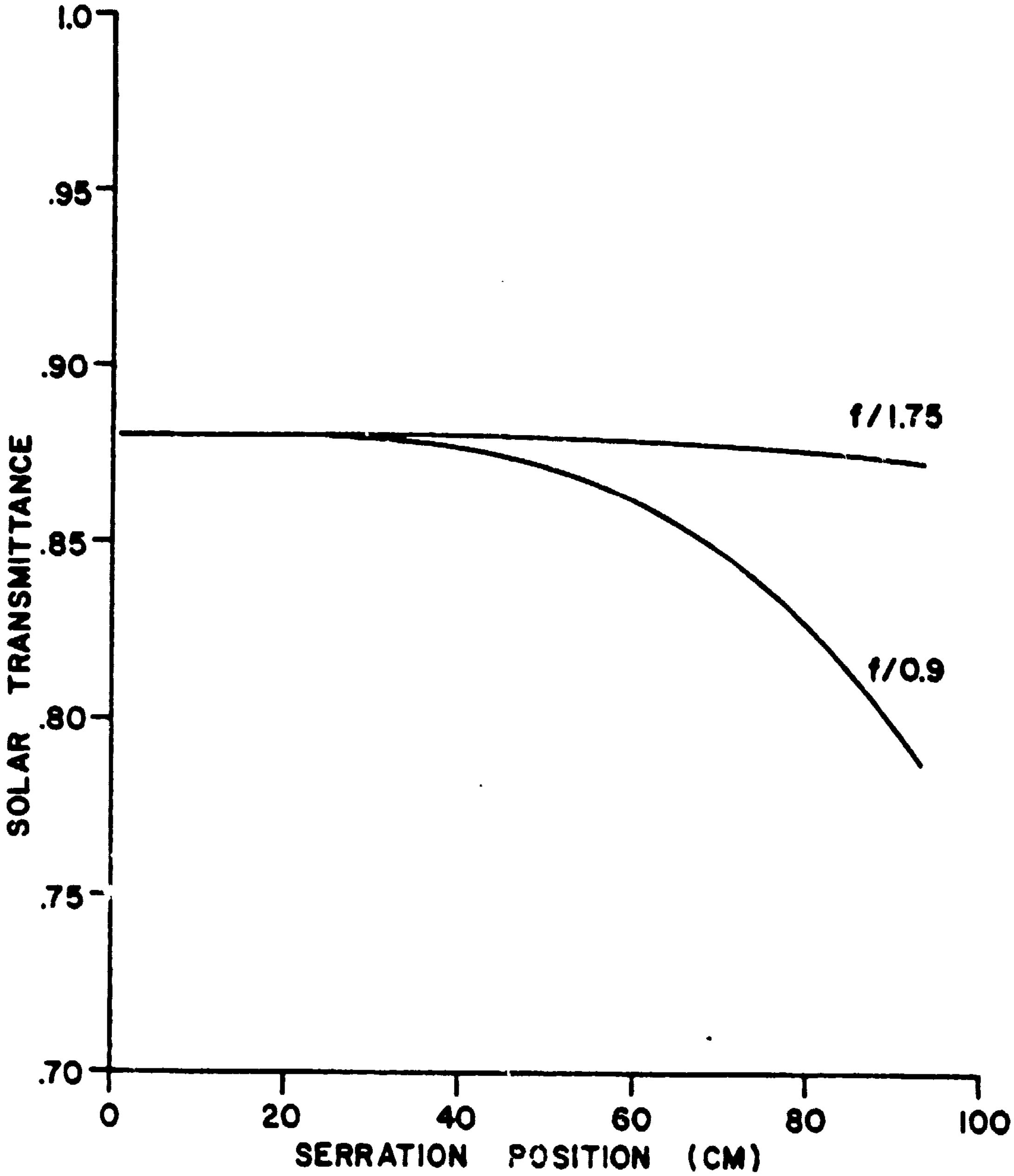

Figure 1. Serration Sunlight Transmittances for Two Perfectly Tracking Lens Concentrators.

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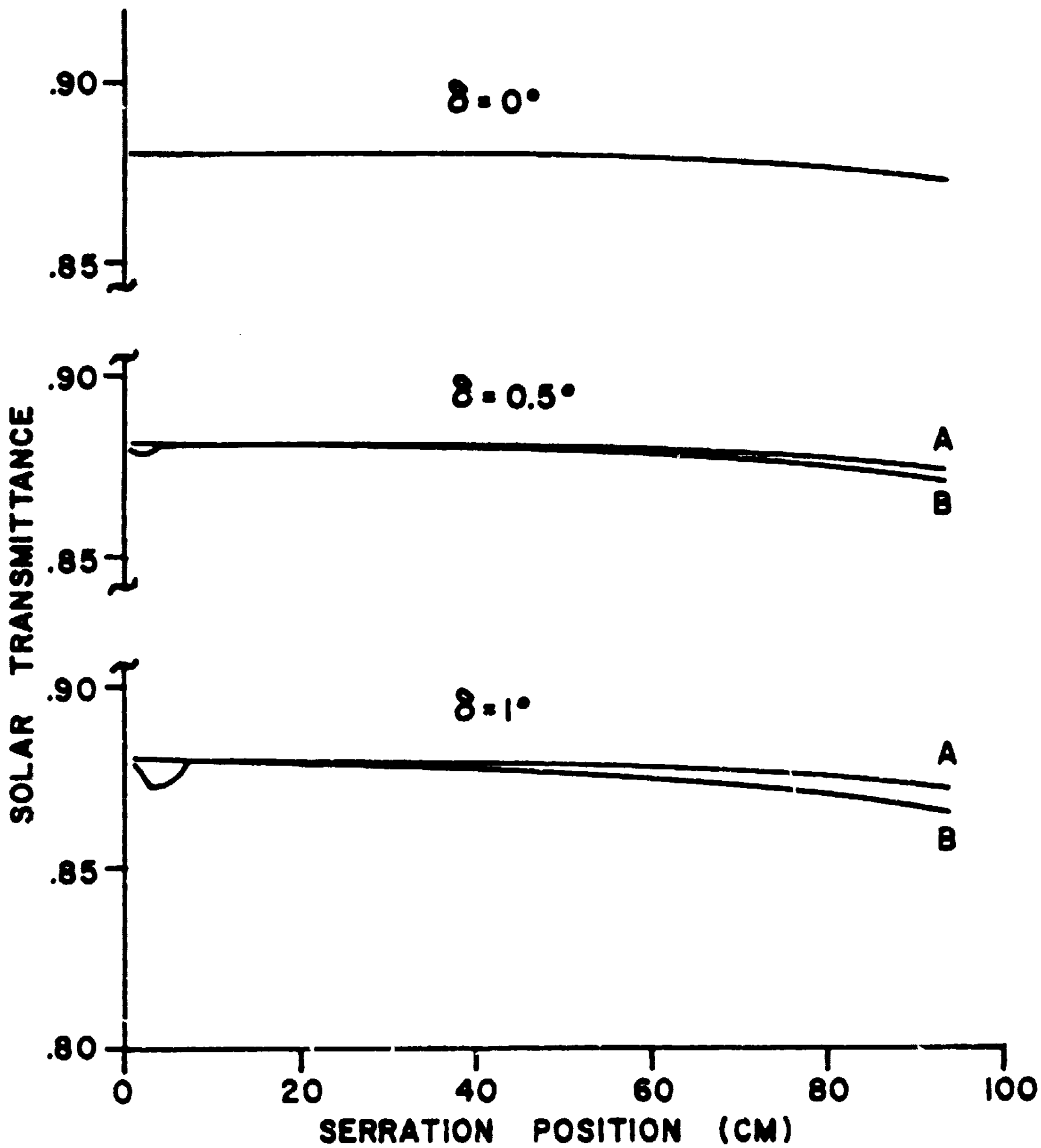

Figure 2. Serration Sunlight Transmittance for an f/1.75 Lens Concentrator With Transverse Tracking Deviations, δ. A - Lower Lens Half; B - Upper Lens Half (or Sunside).

As a measure of the confinement of concentrated energy in the image plane, computerized numerical integration is used to calculate, as a function of target width, the fraction of incident flux intercepted by a target centrally located in the chosen plane. As in Reference 2 and for the reasons discussed there, a reasonable measure of the useful solar localization is the target width required to intercept 78% of the solar flux incident on the lens. Using this target width and intercept fraction a geometric concentration ratio (GCR) may be defined as

$$\text{GCR} = \frac{\text{INTERCEPT FRACTION X LENS WIDTH}}{\text{TARGET WIDTH}} .$$

Quantitative comparisons of the geometric concentration ratio are used in subsequent discussions to evaluate solar concentration performance as a function of f-number.

Note that other intercept fractions could be chosen as the basis for computing the GCR. In that event, intercept fraction versus target width plots can be used to evaluate the geometric concentration ratios.

1. Focal Plane Concentration

a. Perfect Tracking

Focal plane image profiles for perfectly tracking lenses were computed for f-numbers in the range f/0.9 to f/2.0. Example profiles are presented in Figure 3. The maximum local concentration ratio occurred for f/0.9. Low f-number profiles also exhibit a long low intensity "tail". The large f-number profiles exhibit a much more uniform intensity over a broader region. In Figure 4, the geometric concentration ratio is plotted as a function of f-number. The GCR is

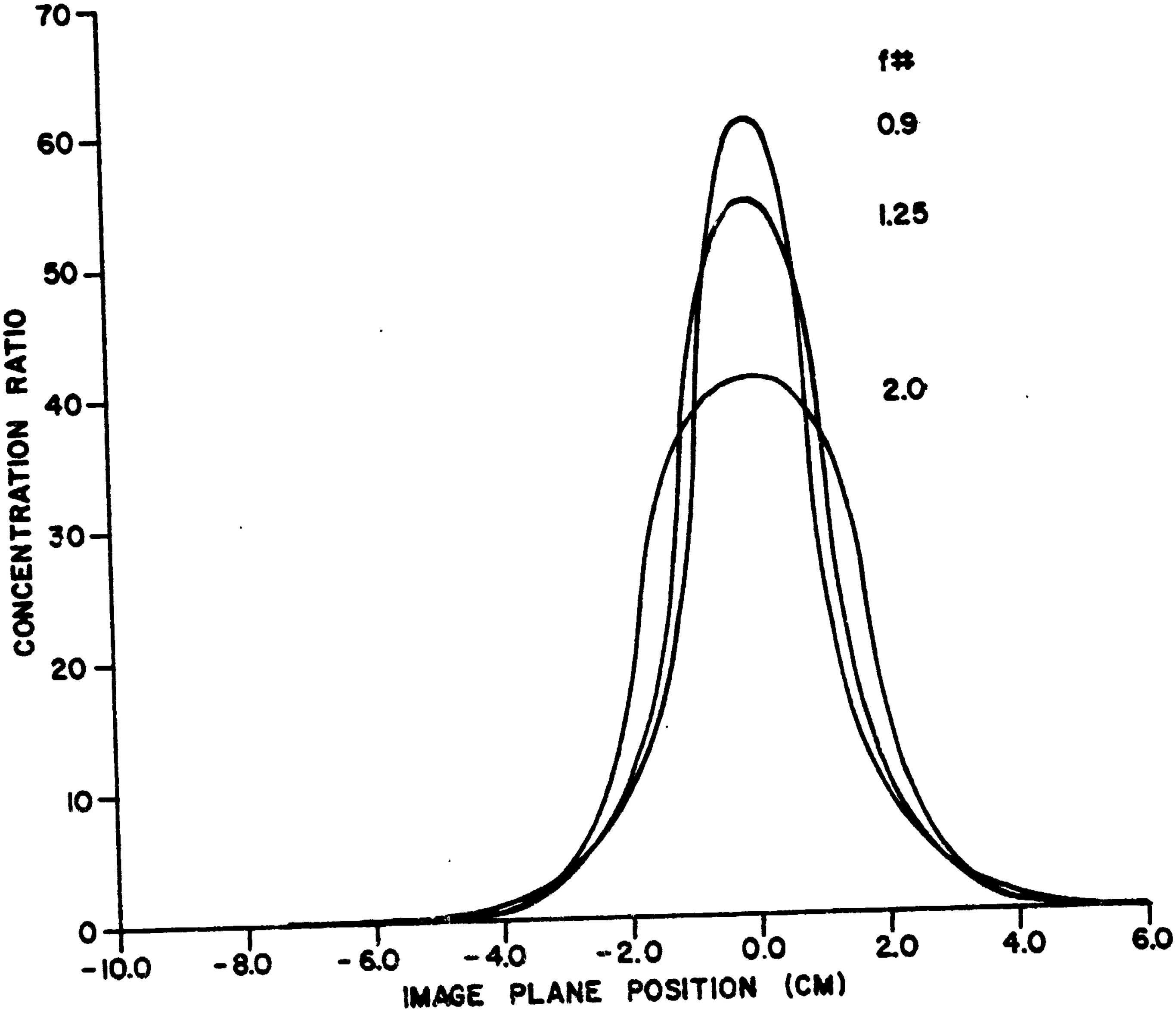

Figure 3. F-Number Effects on Image Intensity Profiles.

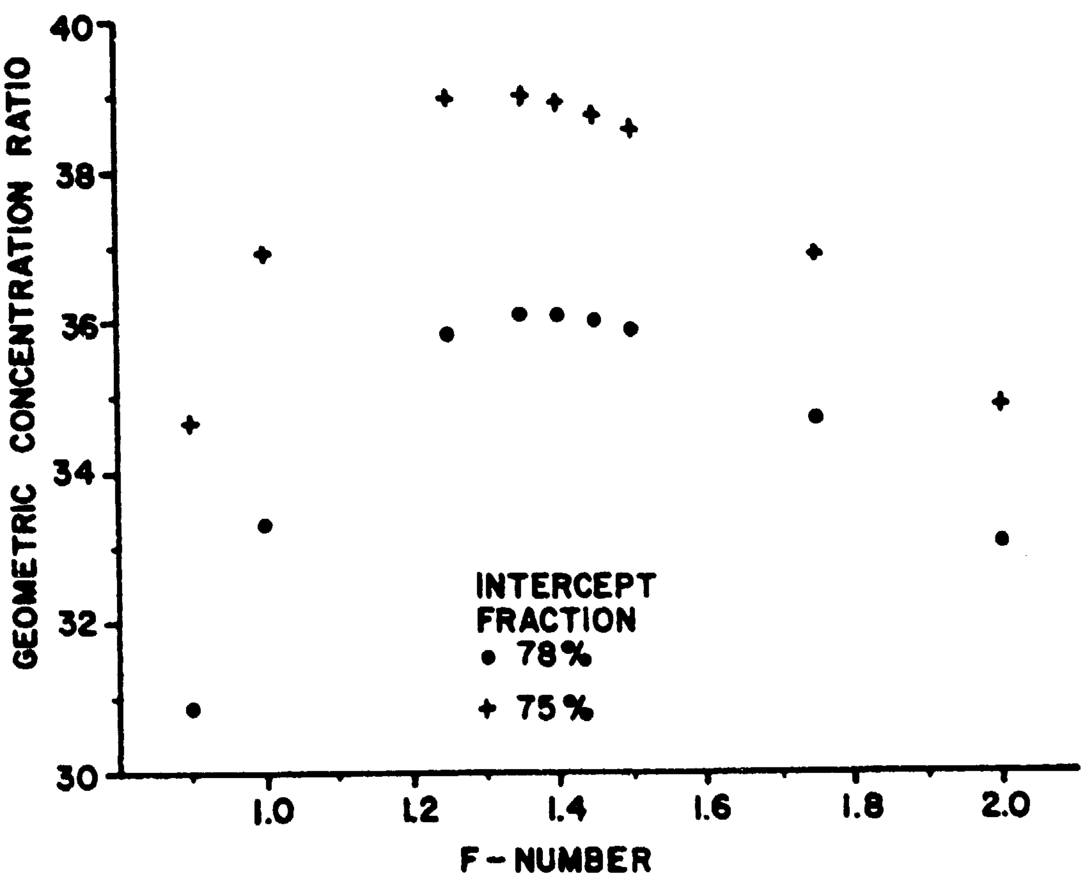

Figure 4. Geometric Concentration Ratio as a Function of Lens F-Number.

observed to peak around f/1.35. Also, the geometric concentration ratio based on 75% target interception of incident solar flux was plotted for comparison. As seen in Figure 4, the data peaks coincide (within the limits of resolution imposed by the number of data points), and the functional dependence on f-number is very similar. Therefore, selection of the 78% intercept fraction does not bias the solar performance results and conclusions for perfectly tracking lenses.

b. Effects of Transverse Tracking Deviations

The effects of small transverse tracking errors ($\leq 1°$) on the focal plane image profiles are illustrated in Figures 5, 6, and 7 for f-numbers of 0.9, 1.5, and 2.0, respectively. As noted previously for low f-number lenses [1], profile shift, profile distortion, and peak concentration reduction generally increase with increasing transverse error for the f/0.9 lens. With increasing f-number, the peak local concentration ratio drops for a given tracking error. The rate of peak concentration reduction with increasing tracking error is reduced drastically for the large f-number lenses, with the peak ratio changing only by roughly 1% for an f/2.0 lens with a 1° tracking deviation. Profile distortion with tracking error also occurs for large f-numbers, but is less apparent due to the squat shape of the profiles. Comparing the profiles in the figures, it is evident that profile shift grows substantially as the focal length is increased.

The geometric concentration ratio is displayed as a function of transverse error for f-numbers 0.9, 1.25, and 2.0 in Figure 8. Maximum GCR's occur for the f/1.25 lens over the one degree range of

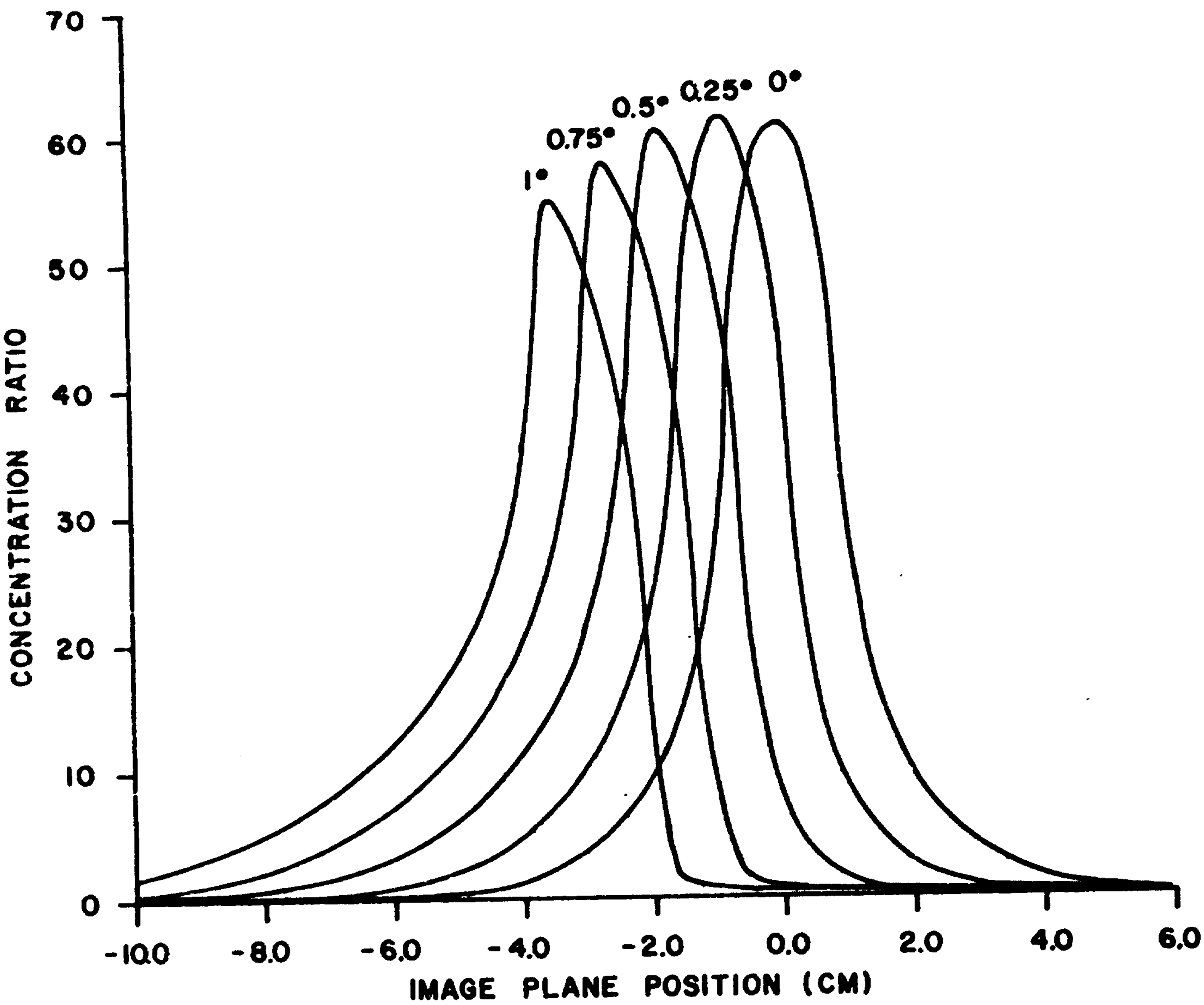

Figure 5. Transverse Orientation Effects on Image Profile for an $f/0.9$ Lens.

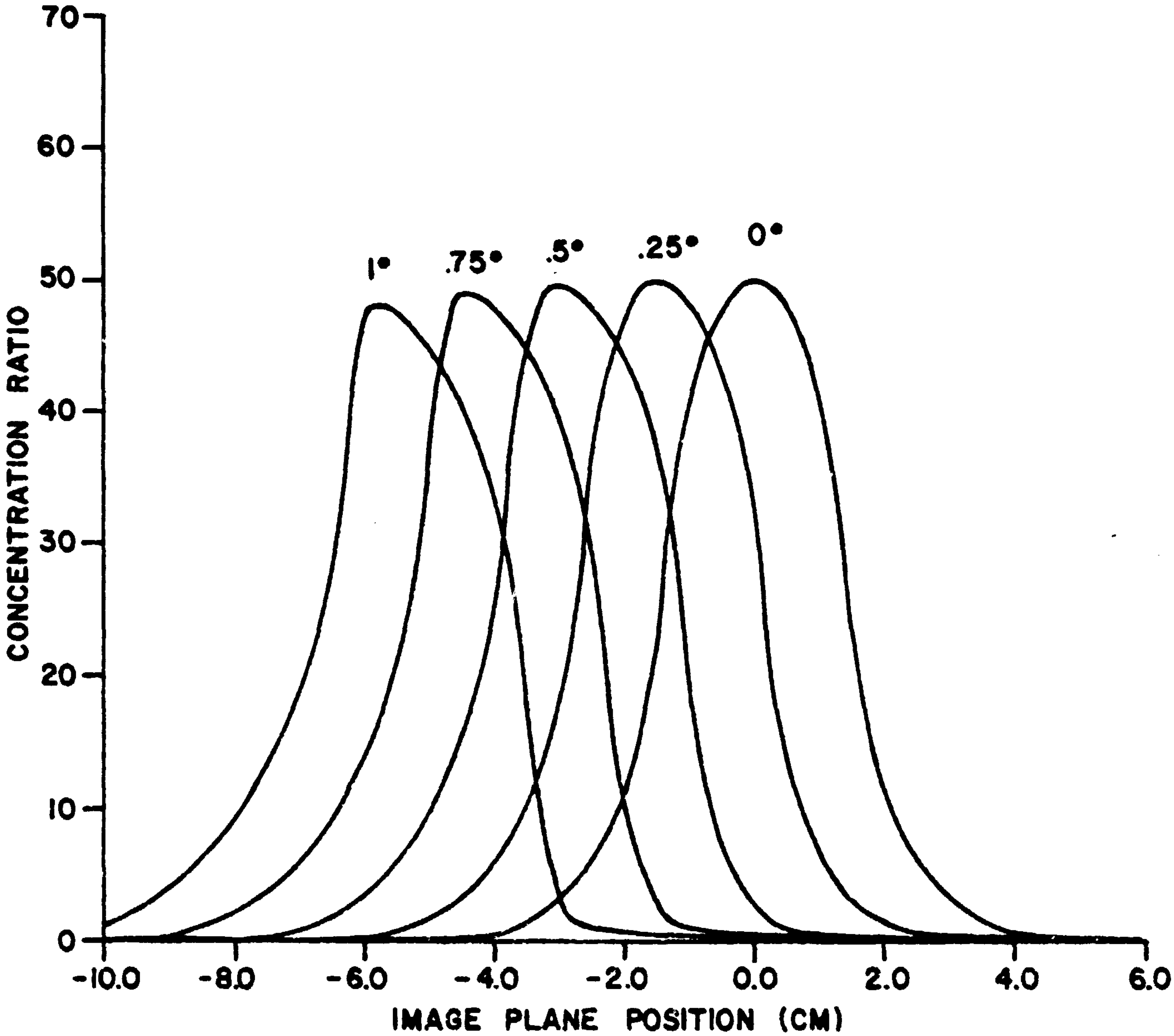

Figure 6. Transverse Orientation Effects on Image Profile for an f/1.5 Lens.

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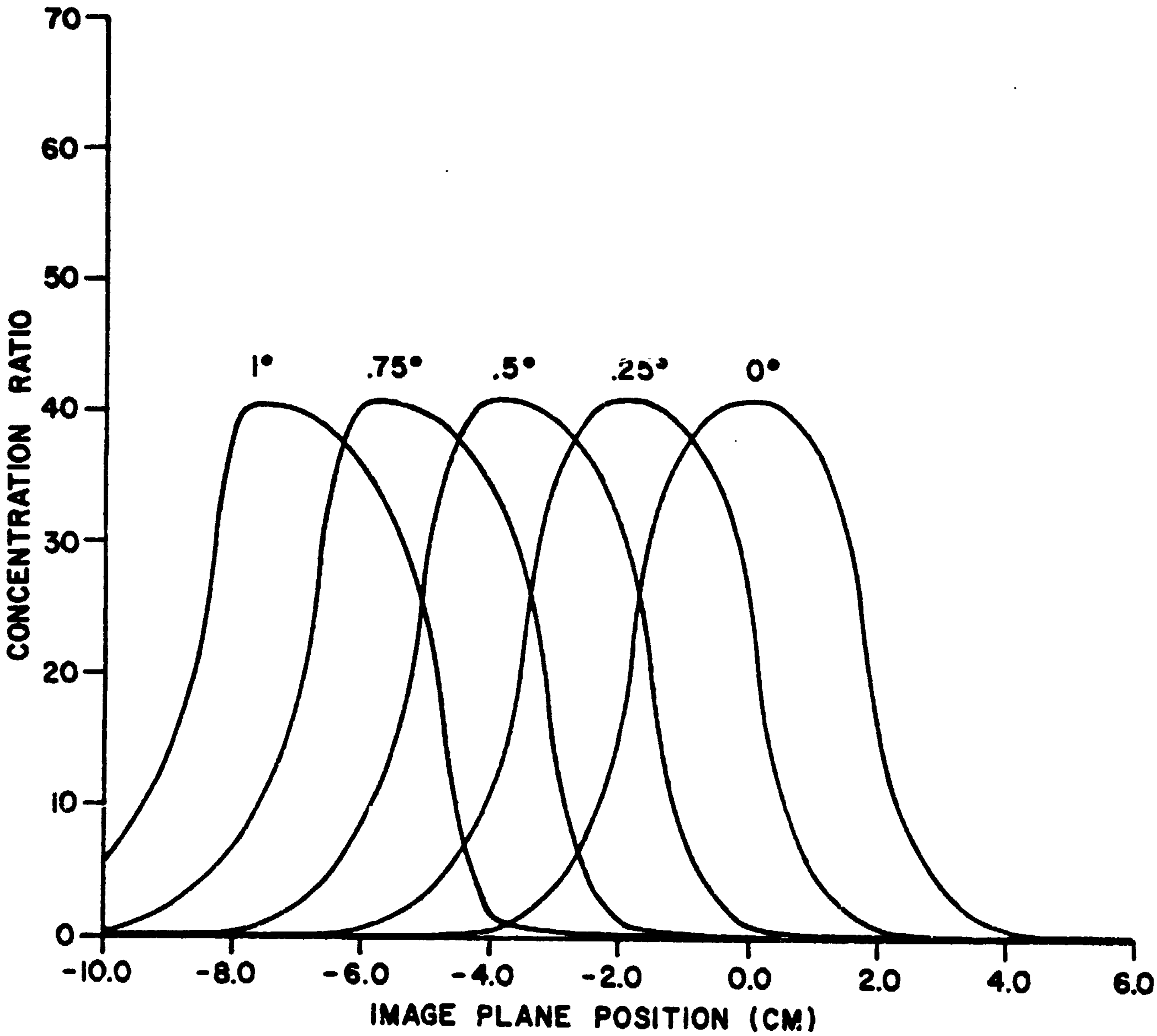

Figure 7. Transverse Orientation Effects on Image Profile for an f/2.0 Lens.

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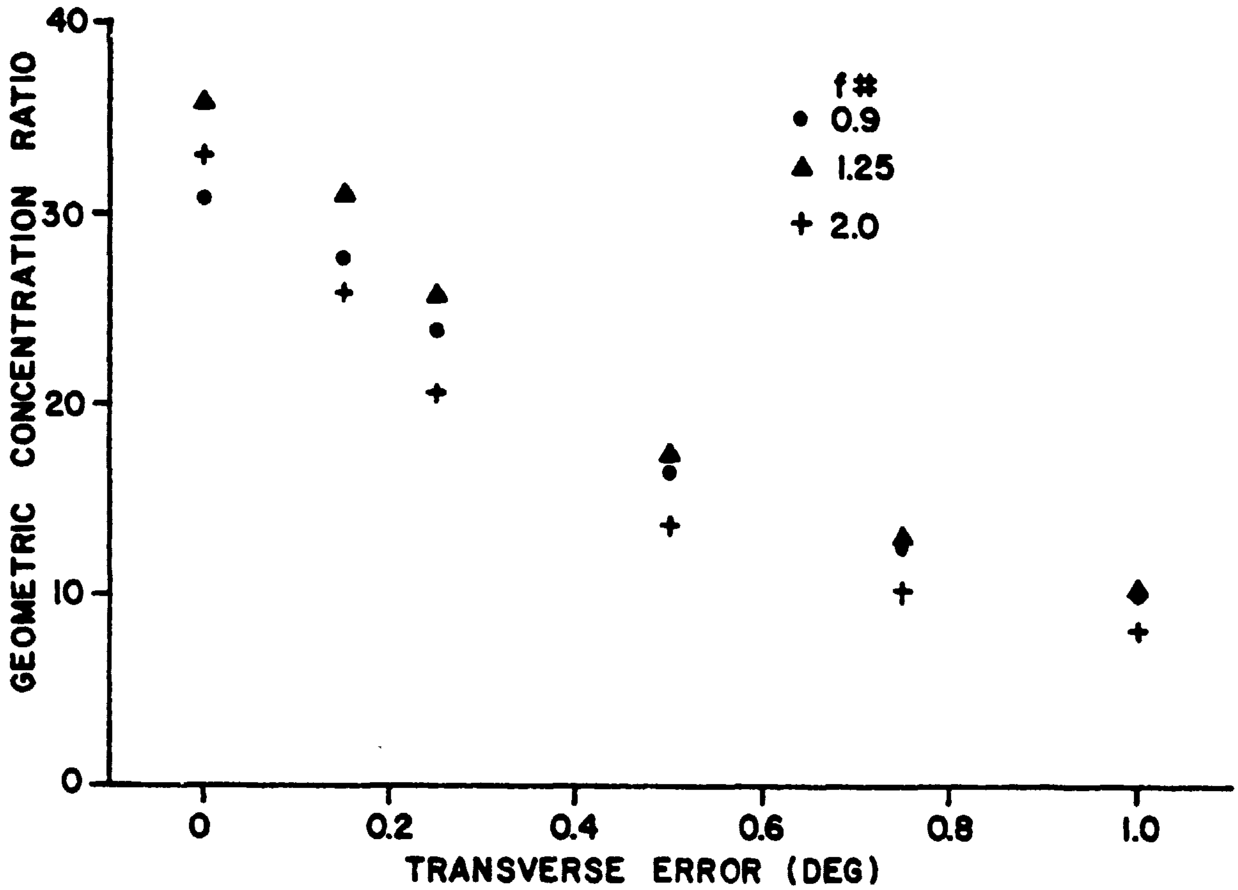

Figure 8. Geometric Concentration Ratio as a Function of Transverse Tracking Error.

tracking error. For the f/2.0 lens, the initial GCR is high but so is the sensitivity to tracking deviation. Suprisingly, the rate of change of the GCR is the least for the f/0.9 lens. These sensitivities are quantified in Figure 9 where the change in the GCR from the perfect tracking value is shown versus transverse error. From the displayed data in the figures, one may conclude that the f/1.25 lens is the optimum choice of the three f-numbers.

In this case, care must be exercised when using the computed GCR's in arriving at conclusions concerning the solar performance in the presence of tracking errors. As illustrated in Figure 10 for f/0.9 and f/1.5 lenses, the relative sensitivities to tracking deviations depends on the selected intercept fraction used for computing the GCR. For a very low intercept fraction, e.g., 0.6, it is clear from the figure that an f/0.9 lens requires a much smaller target than the f/1.5 lens for a given tracking error. For a 78% interception, the f/1.5 lens is superior for tracking errors less than 0.5°.

2. Extra-Focal Plane Concentration

The rate of change in image profile characteristics as the chosen image plane recedes from the focal plane determines the care with which the target receiver must be positioned relative to the lens plane. In Figures 11 and 12, the image profiles for f/0.9 and f/1.5 lenses are illustrated for defocusing percentages of +1%, -1%, and -2% where (+) denotes movement of the image plane away from the lens and (-) toward the lens. Relative to the focal plane profile, concentration is increased for +1% defocusing for both examples, as observed in previous studies [4]. As shown in Figure 13, the geometric concentration ratio actually

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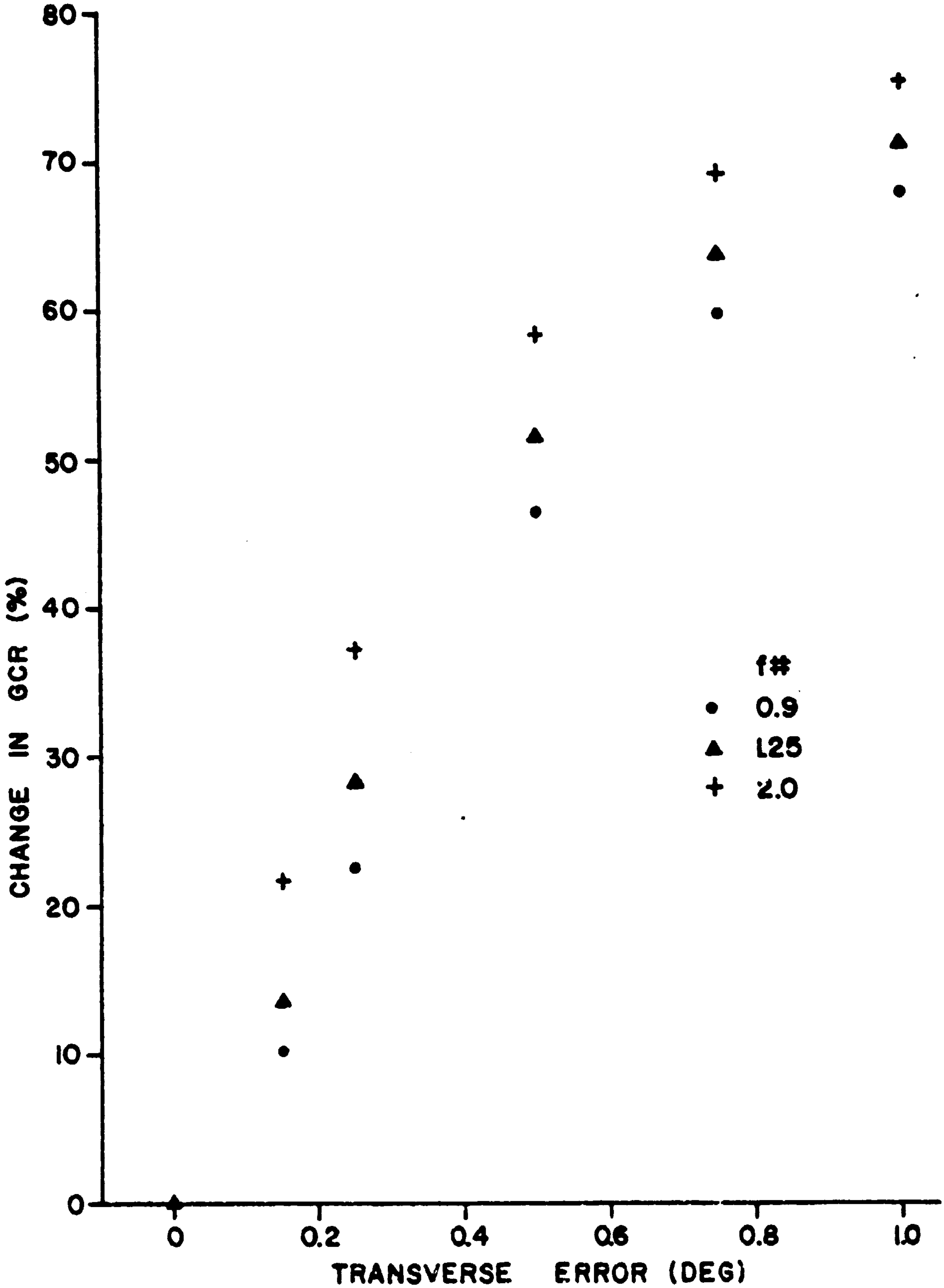

Figure 9. Percentage Change in Geometric Concentration Ratio from the Perfect Tracking Value Plotted as a Function of Transverse Error.

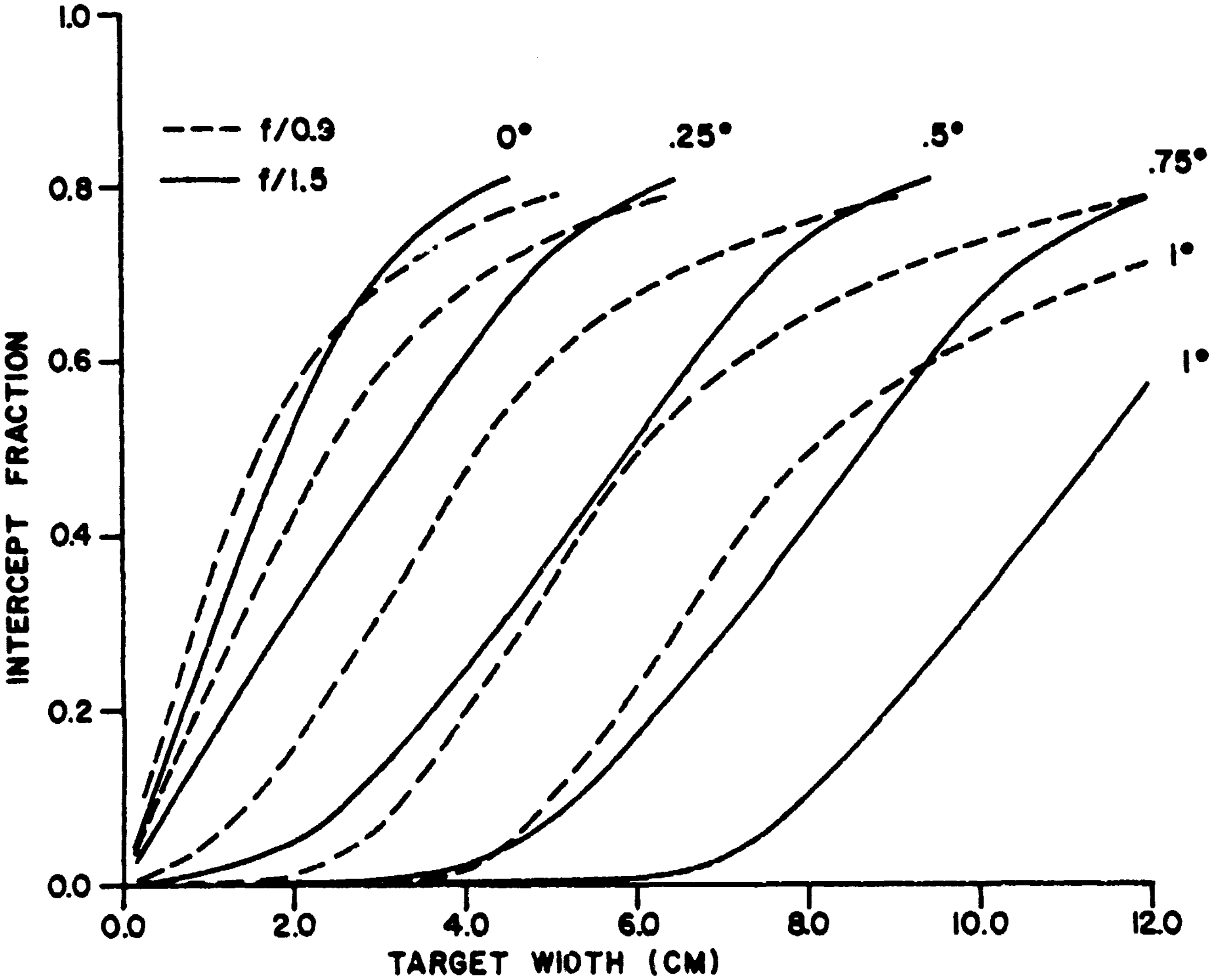

Figure 10. Fraction of Incident Sunlight on the Lens Intercepted by a Target Receiver in the Image Plane. Variations for Transverse Tracking Errors Up to 1° are Shown.

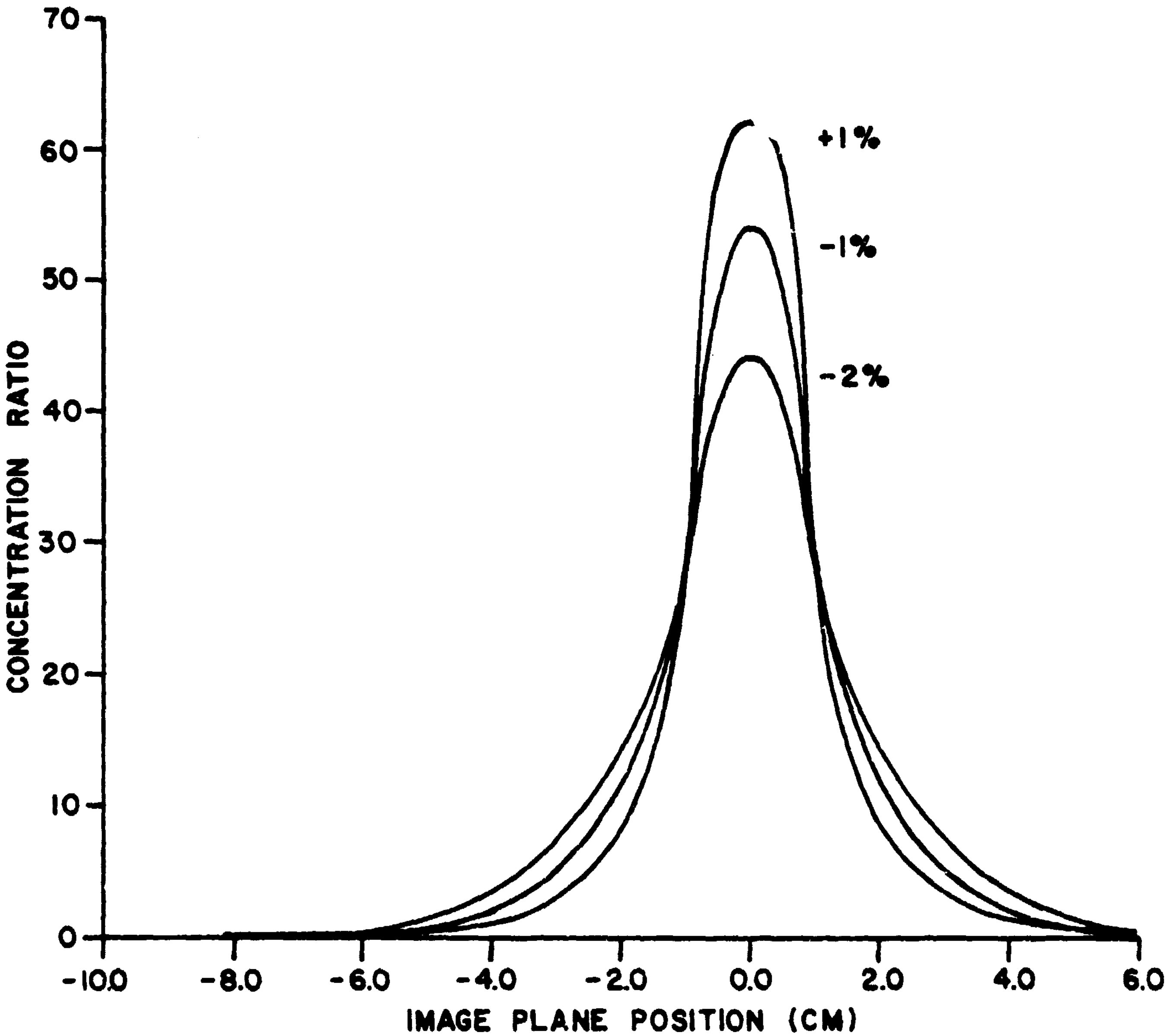

Figure 11. Defocused Intensity Profiles Above (-) and Below (+) the Focal Plane for an f/0.9 Lens.

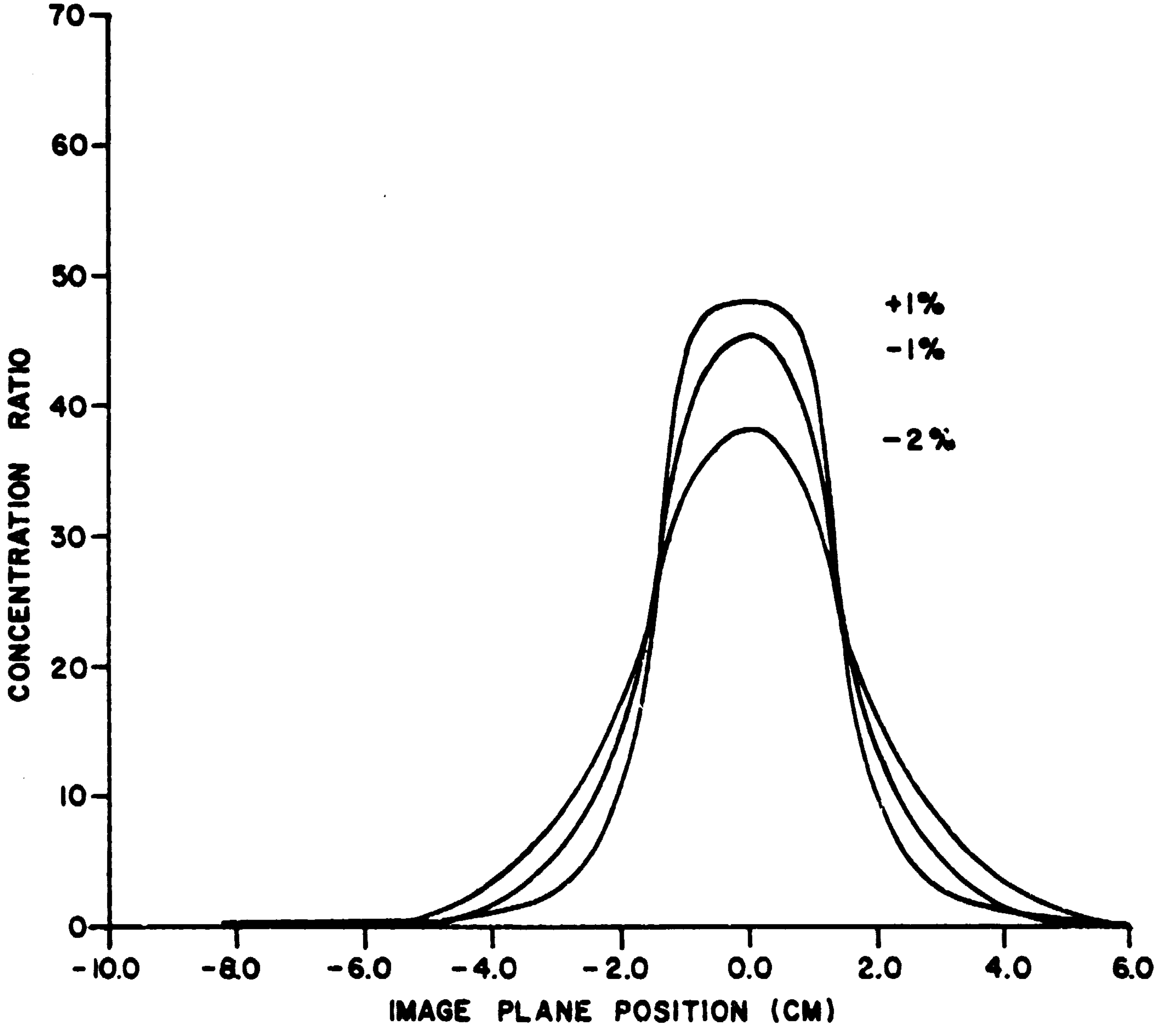

Figure 12. Defocused Intensity Profiles Above (-) and Below (+) the Focal Plane for an f/1.5 Lens.

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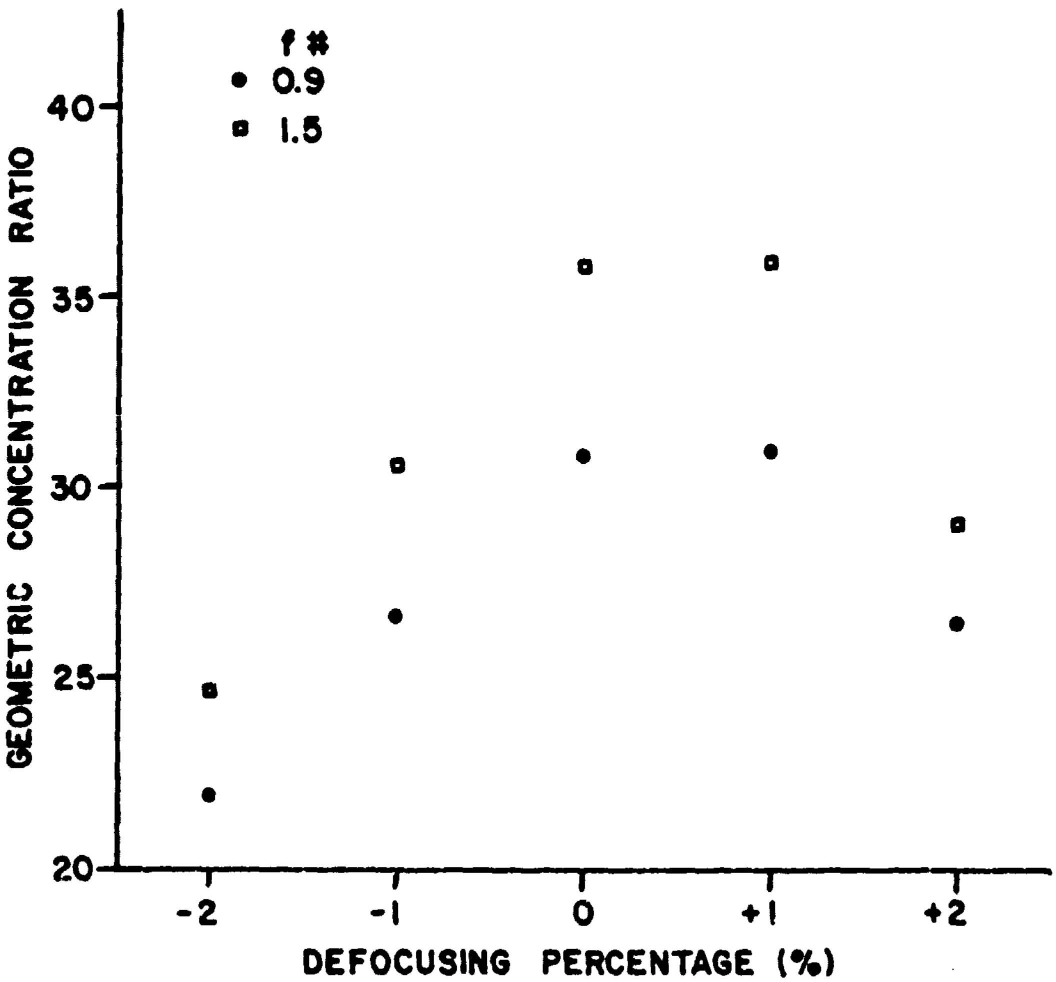

Figure 13. Effects of Slight Defocusing on the Geometric Concentration Ratio.

peaks between 0 and +1% defocusing. Relative to this optimum, the image profiles broaden and the peak concentration drops. The rate of decrease in the GCR is larger for the f/1.5 lens than the f/0.9 concentrator. Although additional data is needed for definitive conclusions, it seems apparent that the greatest sensitivity to defocusing occurs at the f-number demonstrating the highest GCR, i.e., approximately f/1.35.

C. Simulation of Experimental Method For Varying F-Number

In experimental studies, the f-number of a test lens can be increased by covering outer lens sections, thereby changing the width of the lens rather than the focal length. Using the analytical model and a revised computer program, this procedure has been simulated for an ideal lens with the characteristics of the large-scale NASA test lens. Data was generated for effective f-numbers of 0.9, 1.0, 1.25, 1.5, 1.8, and 2.0. The f/1.8 lens corresponds to covering the outer 18 inch panels.

Figures 14 thru 19 display example results. Lens transmittance varied from 86.0% to 88.0% for perfectly tracking lenses with f/0.9 to f/2.0. Serration solar transmission is plotted in Figure 14 for the f/1.8 lens. Image profiles for perfectly tracking lenses (Figure 5) exhibit the reduction in total intercepted energy with increasing f-number. The GCR again maximizes at roughly f/1.35, as demonstrated in Figure 16. Transverse tracking error effects on geometric concentration ratios are illustrated in Figure 17. Focal plane image profiles for the f/1.8 lens with tracking error are displayed in Figure 18. The corresponding intercept fractions as a function of target width are shown in Figure 19.

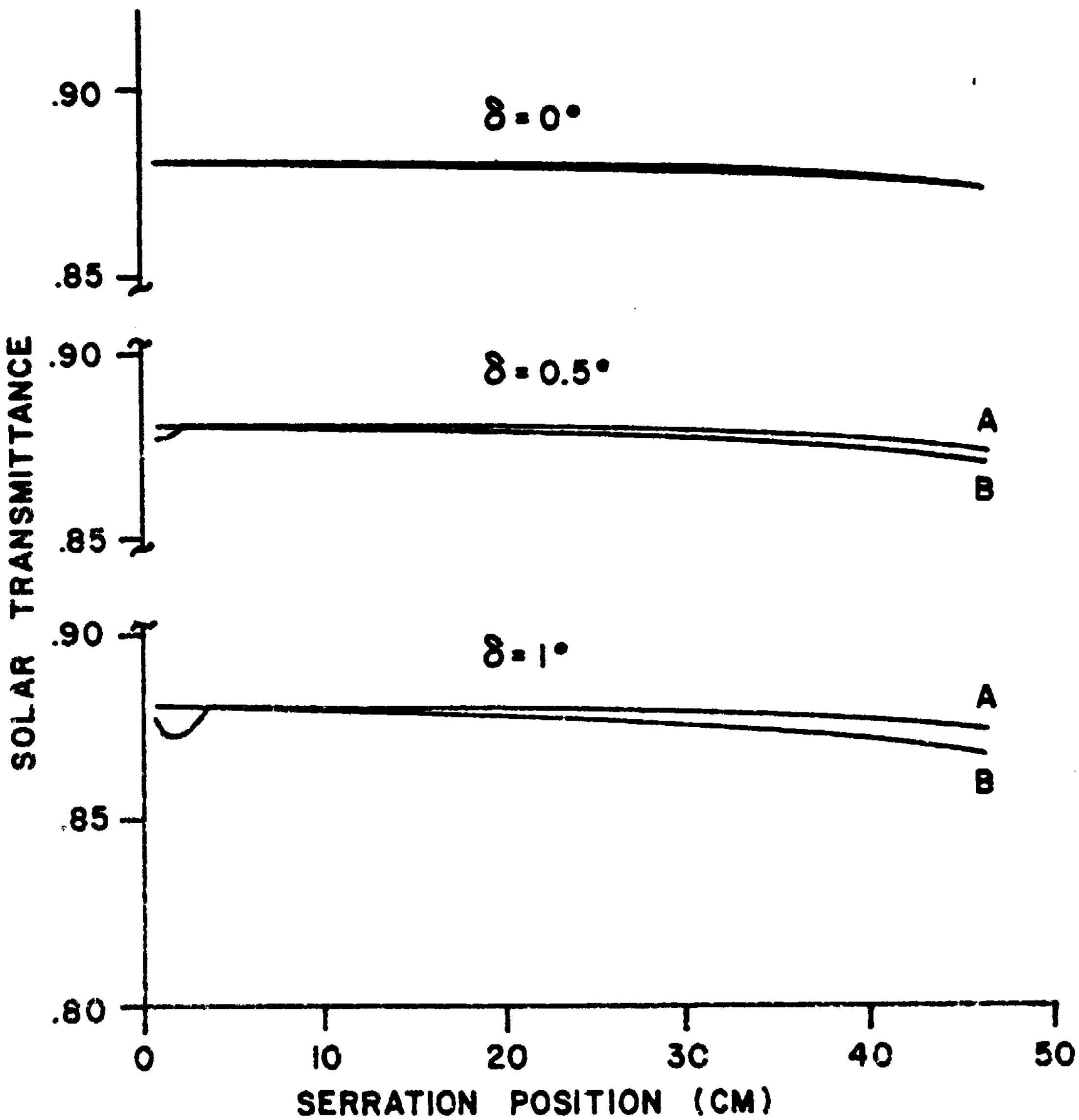

Figure 14. Computed Serration Sunlight Transmittance for Experimental f/1.8 Lens Concentrator With Transverse Tracking Deviations, δ. A - Lower Lens Half; B - Upper Lens Half (Sunside).

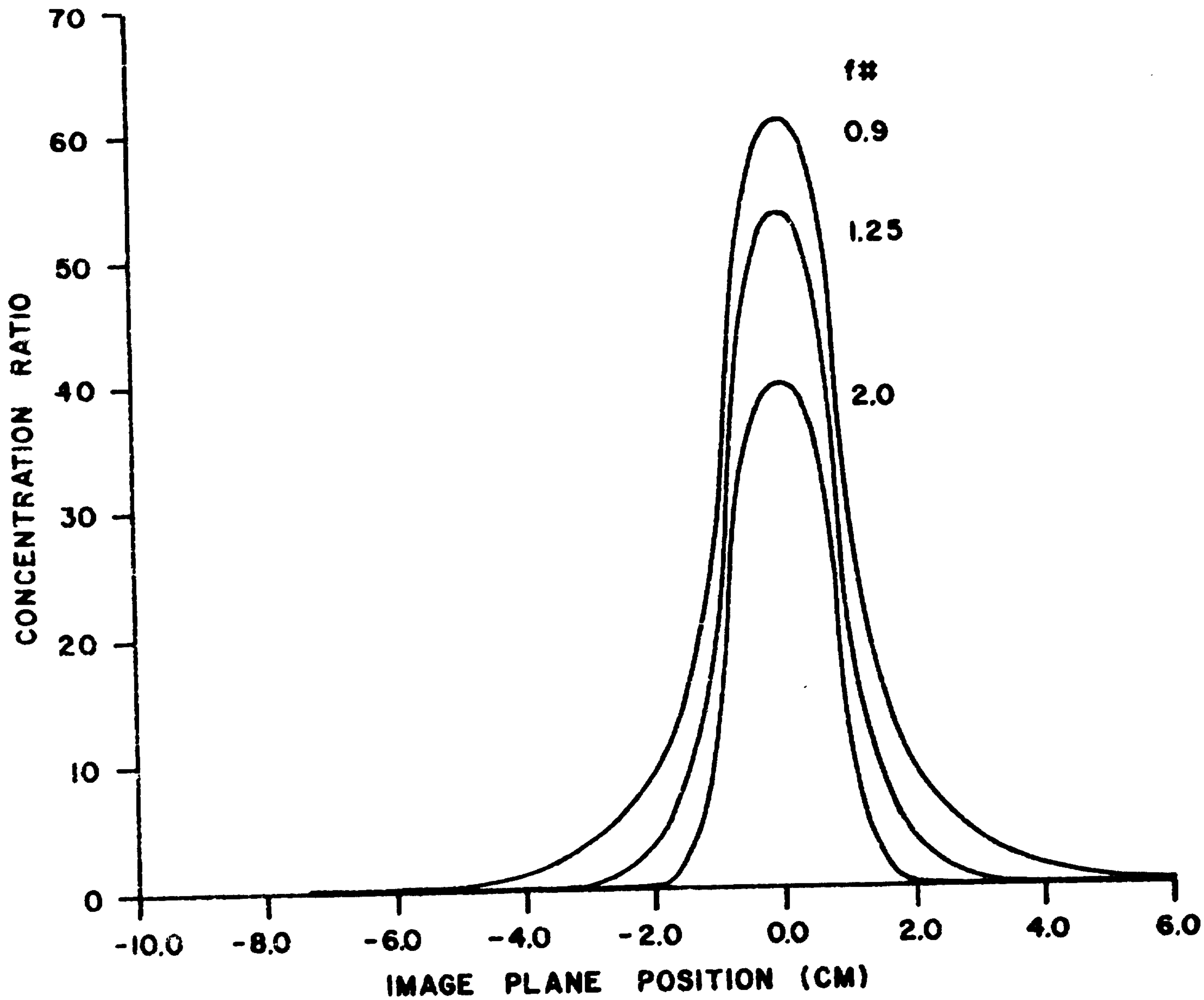

Figure 15. F-Number Effects on Image Profiles Computed for Experimental Lens.

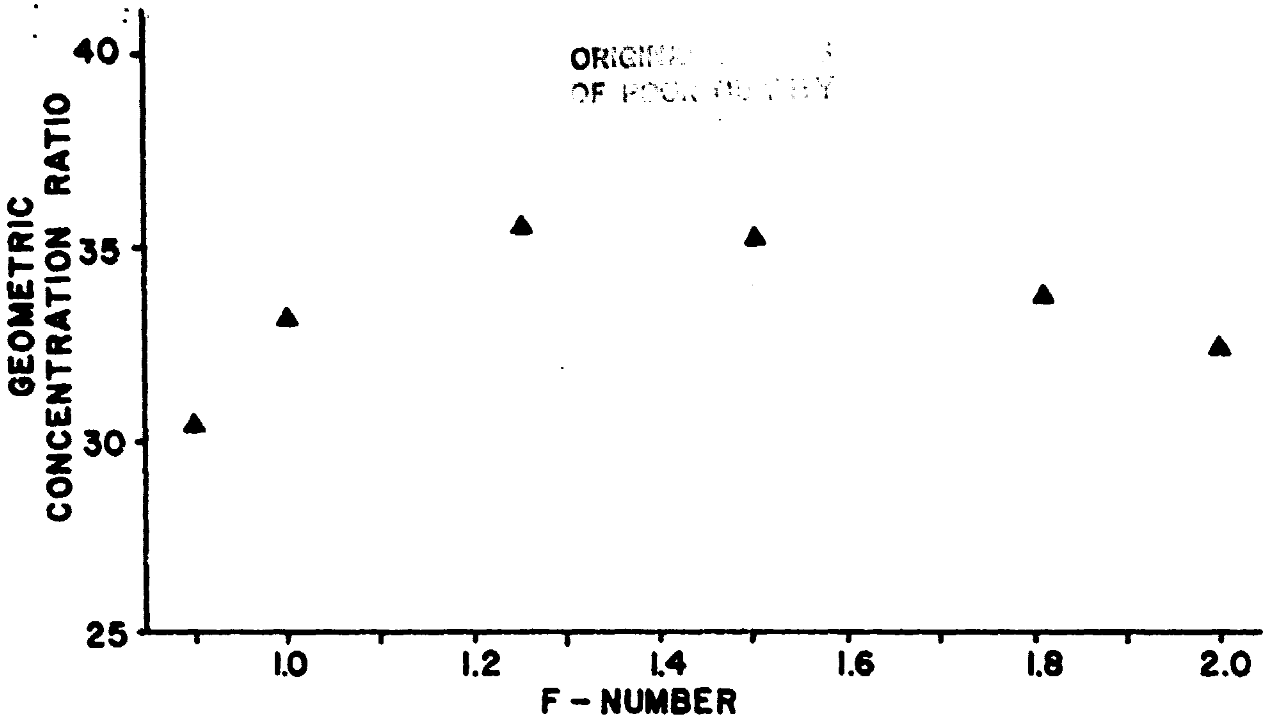

Figure 16. Geometric Concentration Ratio as a Function of Experimental Lens F-Number.

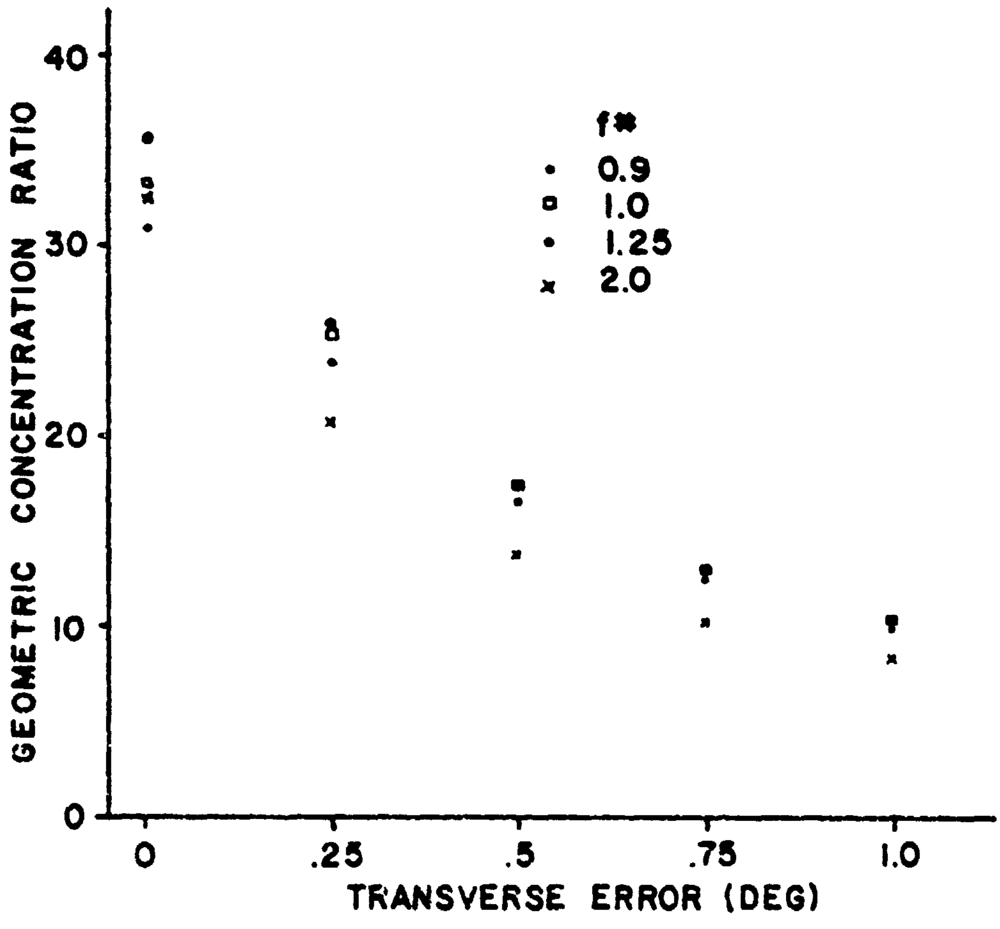

Figure 17. Variation of Geometric Concentration Ratio With Transverse Error for Experimental Lens.

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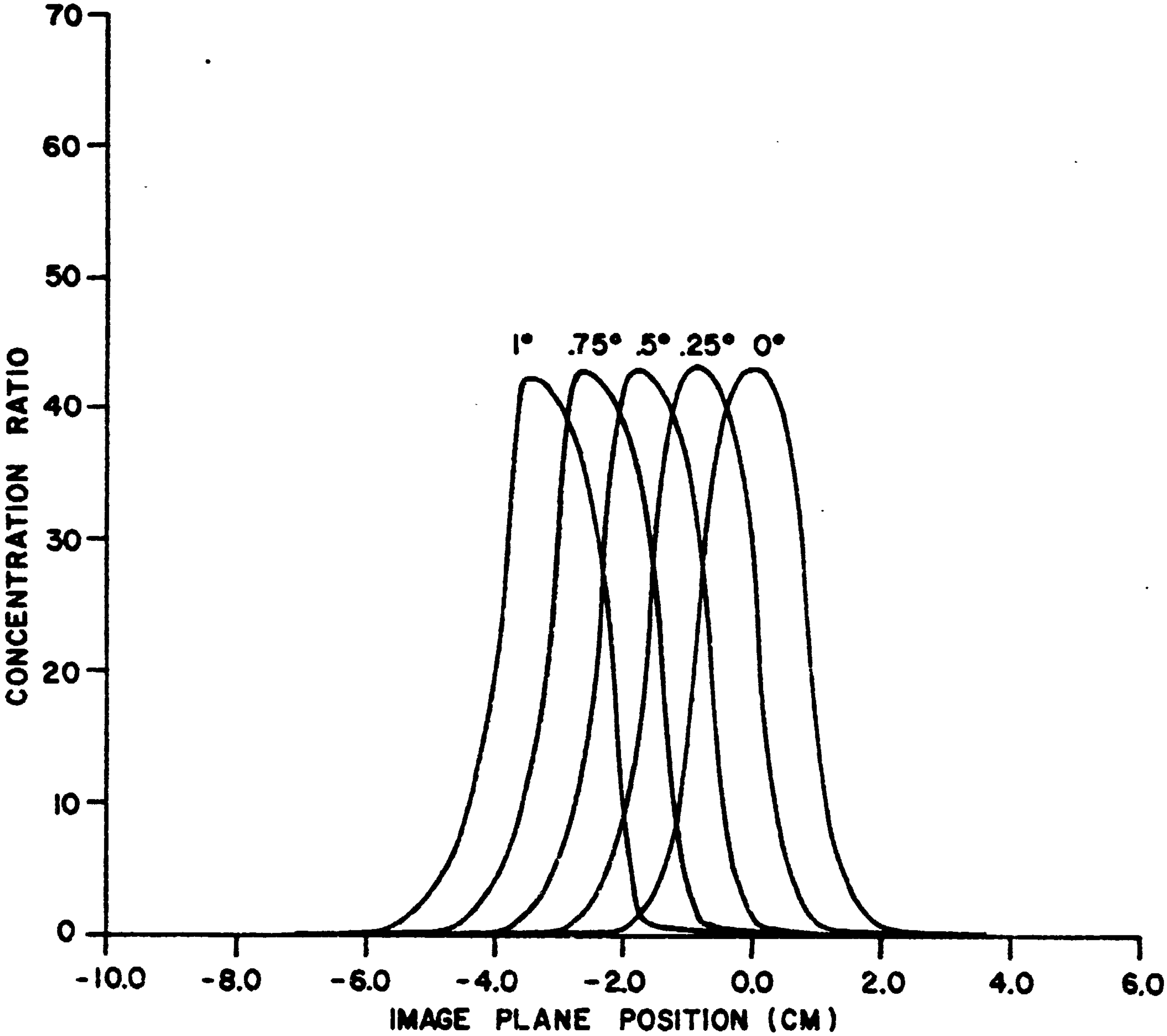

Figure 18. Transverse Orientation Effects on Image Profile Computed for the Experimental f/1.8 Lens.

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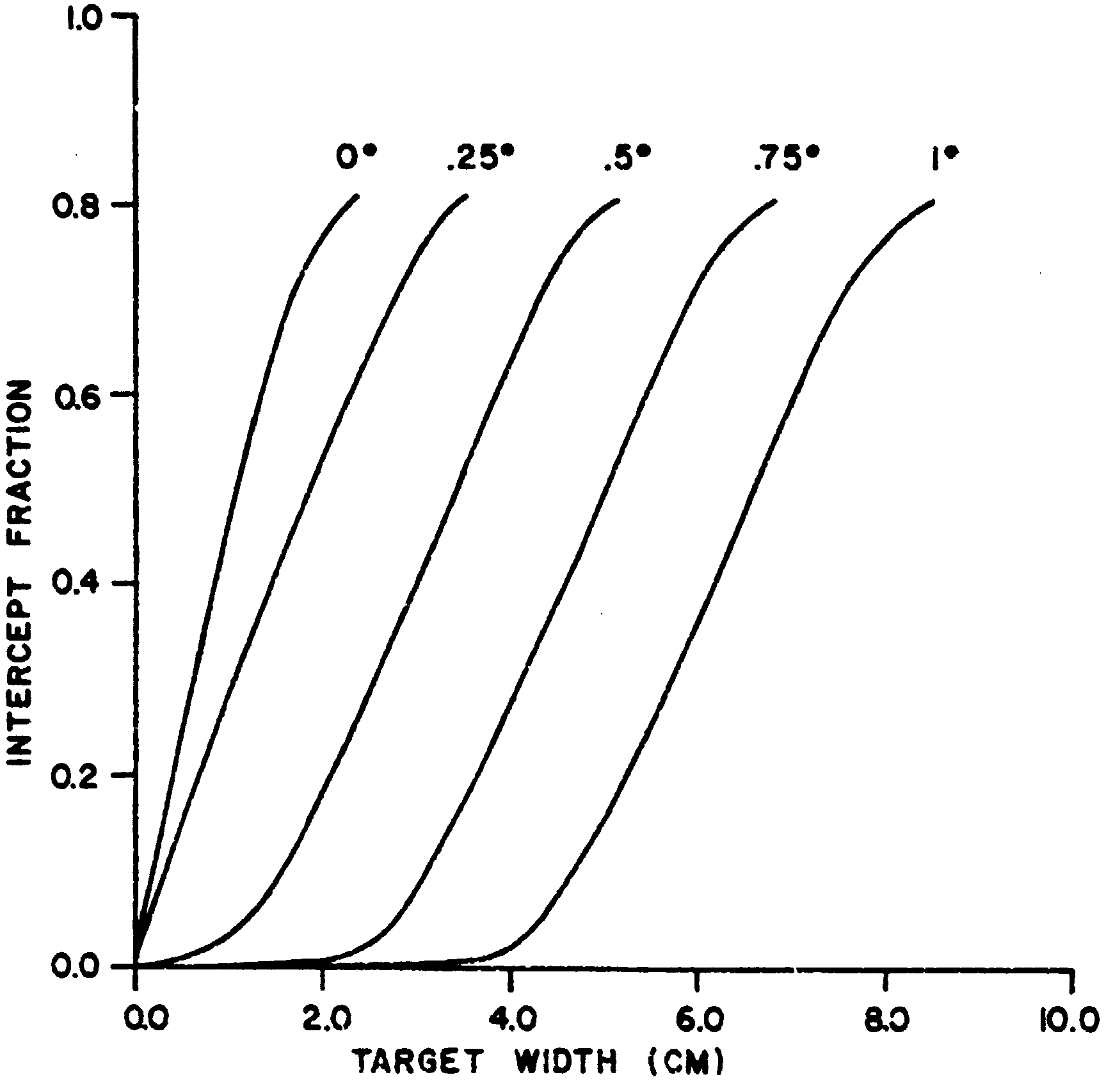

Figure 13. Fraction of Incident Sunlight on the Experimental f/1.8 Lens Intercepted by a Target Receiver in the Image Plane. Variations for Transverse Tracking Errors Up to 1° are Shown.

Since the measured transmittance for the inner 18 inch panels of the NASA test article agreed well with the computed value [3], it is suggested that experimental results for the test lens, with the outer panels covered, be compared carefully with the computed performance characteristics for the f/1.8 case. For this specific case, computed values are listed in Table 2.

Table 2. COMPUTED DATA FOR f/1.8 LENS.

Lens transmittance	0.878
Peak local concentration ratio	43.3
Target Width for 90% intercept of transmitted flux (perfect tracking)	2.19 cm
Target width (78% intercept fraction)	
Perfect tracking	2.11 cm
$\delta = 0.15°$	2.61
0.25	3.23
0.50	4.84
0.75	6.49
1.0	8.16

III. CONCLUSIONS

For flat, linear Fresnel lens concentrators with f-numbers in the range 0.9 to 2.0,

- Lens solar transmittance is high at an average of 87% and changes by less than 2% over the range of f-numbers studied. The decrease in solar transmittance for low f-numbers is due to increased Fresnel reflection at the outer lens serrations.

- Lens solar transmittance is a very weak function of tracking error for transverse errors $\leq 1°$, decreasing by no more than 0.25%.

- As the f-number is increased from f/0.9, the image profiles become less peaked, exhibiting more uniform intensities over the image width.

- Based on a 78% intercept fraction, the geometric concentration ratio for perfectly tracking lenses maximizes near an f-number of 1.35.

- For small transverse errors ($\leq 1°$), profile shift increases with increasing f-number while peak local concentration values become less sensitive to small tracking deviations.

- Small transverse tracking errors result in substantial decreases in geometric concentration ratios for all the lenses. While the rate of decrease is least for the lowest f-number lens, the solar performance is optimized with a larger f-number lens, between f/1.25 and f/1.5, and probably near f/1.35.

- The experimental procedure of covering outer sections of a lens to create larger f-number devices provides an accurate method for testing the effects of f-number on transmittance and geometric concentration ratio, and assessing transverse tracking error impacts. Changes in image profile shape are possibly more difficult to assess.

Apparently, a lens with an f-number near 1.35 displays the optimum overall solar performance, assuming accurate placement of the receiver assembly with respect to the plane of the lens.

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2. R. Cosby, "Solar Concentration By Curved-Base Fresnel Lenses", NASA Contractor Report CR-2890, August, 1977.

3. L. Hastings, S. Allums, and W. Jensen, "An Analytical and Experimental Investigation of a 1.8 by 3.7 Meter Fresnel Lens Solar Concentrator", NASA Technical Paper 1005, August, 1977.

4. L. Hastings, S. Allums, and R. Cosby, "An Analytical and Experimental Evaluation of a Fresnel Lens Solar Concentrator", NASA TMX-73335, August, 1976.